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comment

Selecting tandem partners for silicon solar cells

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Combining silicon and other materials in tandem solar cells is one approach to enhancing the overall power conversion efficiency of the cells. We argue that top cell partners for silicon tandem solar cells should be selected on the basis of their spectral efficiency — their efficiency resolved by wavelength.

Photovoltaic (PV) module efficiency is a key driver of solar electricity cost reduction[1,2], particularly in markets that have high area-dependent balance-of-system costs, like the residential PV market. The efficiencies of commercial PV modules — and, naturally, their constituent cells — have risen dramatically in response: multi-crystalline silicon modules, which make up roughly 60% of the PV market, have jumped from record efficiencies of 15.5% in 2010 to 19.2% in 2015[3]. Additionally, companies such as Panasonic, SunPower, and Kaneka have recently reported large-area monocrystalline silicon cells with efficiencies exceeding 25% (ref. 4). These are nearing the 29.4% theoretical efficiency limit for a silicon cell[5] and may soon reach the oft-claimed 26% practical efficiency limit[6]. To push cell and module efficiencies still higher, the PV industry will need to transition to the only device structure that has successfully surpassed the (single-junction) detailed-balance limit: multi-junctions.

Fortunately, silicon, the dominant PV technology, has many of the characteristics desired of a bottom cell in a tandem, or two-cell multi-junction. It is abundant, efficient, and inexpensive (US\$70–170 m^{-2} for modules), it has a near-ideal bandgap (1.12 eV) for maximum tandem efficiency[7], and there are 60 GW of existing production capacity[8]. III-V tandem cells, which have achieved 31.6% efficiency under one-sun illumination, would seem a natural guide in the development of efficient silicon-based tandems. However, III-V cells leverage epitaxial growth to access a wide range of bandgaps, and the same approach does not easily translate to silicon because of its unique lattice constant and few alloying partners. The challenge, then, is to identify and develop an efficient top cell — which likely will not be epitaxially grown on silicon, may not be grown on silicon at all, and may be polycrystalline — as well as a suitable configuration for coupling it with a silicon bottom cell.

This Comment aims to provide guidance in selecting top-cell partners for silicon-based tandems by introducing the concept of spectral efficiency — power conversion efficiency resolved by wavelength — and using it to calculate the maximum efficiency possible for tandems composed of existing record solar cells.

State of the art

Table 1 summarizes the highest one-sun efficiencies achieved to date for tandems with silicon bottom cells and a range of both top cells and coupling configurations. III-V/silicon tandems have the longest development history and presently top the efficiency chart: a 29.8%-efficient tandem was demonstrated in 2016 by mechanically stacking a 1.8 eV GaInP cell on a silicon heterojunction cell[9]. Mature thin-film PV technologies such as CdTe, CIGS, and amorphous silicon are absent from the chart, as no efficient, wide-bandgap cells have been fabricated. This is due at least in part to a history of viewing crystalline silicon as a competitor in the single-junction PV market and not as a tandem partner in need of a top cell, and thus comparatively little effort has been spent on, for example, CdTe and CIGS devices with bandgaps wider than 1.5 eV (these materials systems allow for tunable-bandgap absorbers). However, one 1.8 eV CdZnTe top cell epitaxially grown on silicon has been reported[10], and similar, polycrystalline cells could in principle be deposited with the existing CdTe manufacturing capacity. All other tandems in Table 1 utilize lead halide perovskite cells. Perovskites are the newest and least mature photovoltaic technology, but, with their wide and tunable bandgaps and rapidly increasing efficiency, they have quickly emerged as another popular top-cell choice for small-area, laboratory devices. A maximum efficiency of 28.0% has been measured using physically separated silicon and perovskite cells coupled with a beam splitter[11]; several groups have reported tandem efficiencies

Table 1 | Record tandem efficiencies achieved for a range of top-cell materials and coupling configurations.

Top-cell material	Bandgap (eV)	Efficiency (%)	Year	Group/institute	Coupling
III-V					
AlGaAs	1.6	25.2	2012	Univ. Tokyo (ref. 19)	Two-terminal; fusion bonding
AlGaAs	1.6	21.2	1998	Nagoya Inst. Tech. (ref. 20)	Two-terminal; epitaxial growth
GaInP	1.8	29.8	2016	NREL (ref. 9)	Four-terminal; mechanical stack
II-VI					
CdZnTe	1.8	16.8	2010	EPIR Tech. (ref. 10)	Two-terminal; epitaxial growth
Perovskite					
$CH_3NH_3PbI_3$	1.6	19.2	2016	EPFL (ref. 12)	Two-terminal; direct deposition
$CH_3NH_3PbI_3$	1.6	22.8	2015	EPFL (ref. 21)	Four-terminal; mechanical stack
$CH_3NH_3PbI_3$	1.6	28.0	2015	Kaneka (ref. 11)	Four-terminal; optical coupling
$CH_3NH_3PbBr_3$	2.3	23.4	2015	UNSW (ref. 22)	Four-terminal; optical coupling

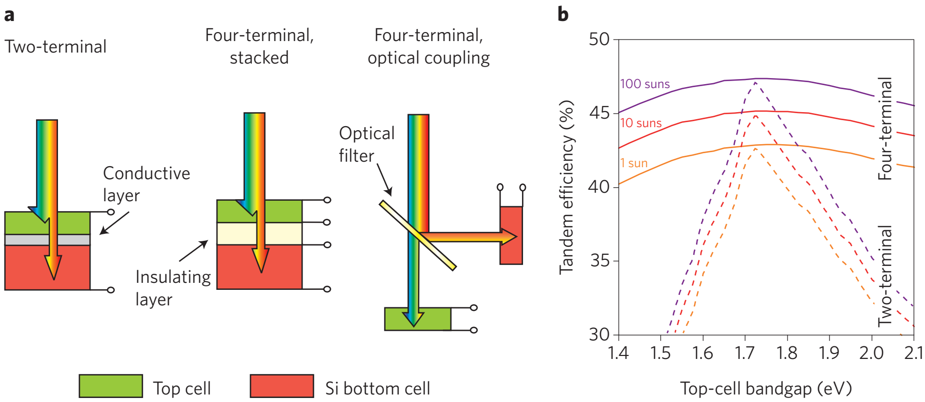

Figure 1 | Limiting efficiencies of silicon-based tandem PV cells. **a**, Three common coupling configurations. The coloured arrows show how the solar spectrum is transmitted and absorbed by the top and bottom cells. **b**, Limiting efficiency of a silicon-based tandem PV cell for varying top-cell bandgap. Efficiencies are shown for two- and four-terminal configurations, as well as three illumination intensities. The silicon cell's current–voltage characteristic was calculated with a model that includes Auger recombination and Lambertian light trapping[5]; the top cell's characteristic was calculated with a detailed-balance model that considers radiative recombination only. The efficiency of the four-terminal tandem was calculated by summing the maximum power of the individual sub-cells and normalizing to the input power; the efficiency of the two-terminal tandem was similarly calculated but using the power generated by both sub-cells at the maximum-power current of the limiting sub-cell.

of around 20% with geometries more compatible with flat-plate PV modules[12,13].

Table 1 hints that, among record laboratory cells, four terminals are better than two (compare, for example, the two tandems made by EPFL with the same sub-cells). This can be understood by examining the common coupling configurations illustrated in Fig. 1a. In two-terminal configurations, the sub-cells are connected in series and their currents must be matched at their maximum power points to avoid power loss. In four-terminal configurations, by contrast, the power output of each sub-cell is measured independently. Removing the current-matching constraint means that precise control of the top-cell bandgap and thickness, front-surface reflection, and parasitic absorption in supporting layers is no longer required. Moreover, four-terminal tandems in the field are expected to have an energy yield a few per cent higher than equivalent-efficiency two-terminal tandems because they are insensitive to current mismatch resulting from spectrum variation[14,15]. Four-terminal configurations also allow for two monocrystalline sub-cells to be paired without epitaxial growth and without necessitating the clean, mirror polished surfaces demanded by bonding, or for sub-cells that have incompatible processing temperatures or chemistries to be paired. Despite these apparent advantages, no four-terminal tandem has been commercialized; III-V concentrator and space multi-junction cells, as well as thin-film silicon tandems, are monolithic two-terminal devices. Commercial four-terminal tandems are expected to have higher module and balance-of-systems costs than their two-terminal cousins, as well as greater power losses when scaling to module-sized areas, and the jury is out as to whether the value of increased efficiency in future markets will outweigh the cost of increased complexity.

Efficiency limits

What efficiency might a silicon-based tandem be expected to reach? A top-down approach to this question begins by calculating the limiting efficiency, which others have done using a detailed-balance model that considers only radiative recombination[16]. A more accurate treatment of the indirect-bandgap silicon bottom cell must also include Auger recombination and incomplete photon absorption[5], however, and thus Fig. 1b shows the limiting efficiency of a tandem comprised of a radiative-recombination-limited top cell of variable bandgap and an Auger-recombination-limited silicon bottom cell with Lambertian light trapping. For a two-terminal configuration, a top cell with a bandgap of approximately 1.7 eV is best, and the tandem has a limiting efficiency of 43% under one-sun illumination. For the reasons discussed above, four-terminal configurations are less sensitive to the bandgap of the top cell but also have peak efficiencies near 1.7 eV. Were tandem cells to reach the same level of maturity as monocrystalline single-junction PV technologies such as silicon and GaAs, which have achieved cell efficiencies that are more than 85% of their respective limits, they would operate with over 36% efficiency.

Spectral efficiency

A different, bottom-up approach to assess the potential of silicon-based tandems is to ask: what would happen if two existing sub-cells were paired? Which cells should one choose and what efficiency is possible? The limiting efficiency calculations used to generate Fig. 1b, which consider hypothetical, ideal cells, are no help here. Instead, we turn to a little-known concept called spectral efficiency[17,18], denoted $\eta(\lambda)$ and defined as:

$$\eta(\lambda) = \frac{V_{OC}\,\mathrm{FF}\,J_{SC}(\lambda)}{I(\lambda)} \qquad (1)$$

with V_{OC} the open-circuit voltage, FF the fill factor, λ the wavelength, $I(\lambda)$ the spectral irradiance (in W m^{-2} nm^{-1}), and $J_{SC}(\lambda)$ the short-circuit current density per unit wavelength (in A m^{-2} nm^{-1}):

$$J_{SC}(\lambda) = q\,\frac{\lambda}{hc}\,\mathrm{EQE}(\lambda)\,I(\lambda) \qquad (2)$$

In equation (2), q is elementary charge, h is Planck's constant, c is the speed of light, and EQE(λ) is the external quantum efficiency. Equation (1) looks like the usual definition of PV cell efficiency, but it is spectrally resolved. Spectral efficiency depicts efficiency at each wavelength and — in analogy with EQE and J_{SC} — its spectrum-weighted integral is cell efficiency. To calculate spectral efficiency, one needs only a current–voltage (J–V) characteristic and EQE spectrum, and thus it is possible to find the spectral efficiency of, for example, the record cells in the solar cell efficiency tables[4].

Figure 2a displays the spectral efficiencies of several record PV cells, including potential bottom cells such as silicon and CIGS, and potential top cells ranging from GaAs to perovskites. Figure 2b displays the limiting spectral efficiencies of cells with a range of bandgaps. Each spectral efficiency curve peaks near the absorber's bandgap wavelength; longer wavelengths are not absorbed and result in zero efficiency, and shorter wavelengths are converted with lower efficiency because of carrier thermalization. The utility of spectral efficiency in designing tandems is that cells of different technologies can be directly compared, and that the benefit of diverting photons from silicon to a candidate top cell is visually apparent. For example, Fig. 2a reveals that, even though a-Si:H has the ideal bandgap for a top cell, the best a-Si:H cell converts every wavelength to electricity with poorer efficiency than the best monocrystalline silicon cell, and thus their tandem will necessarily perform less well than the bottom

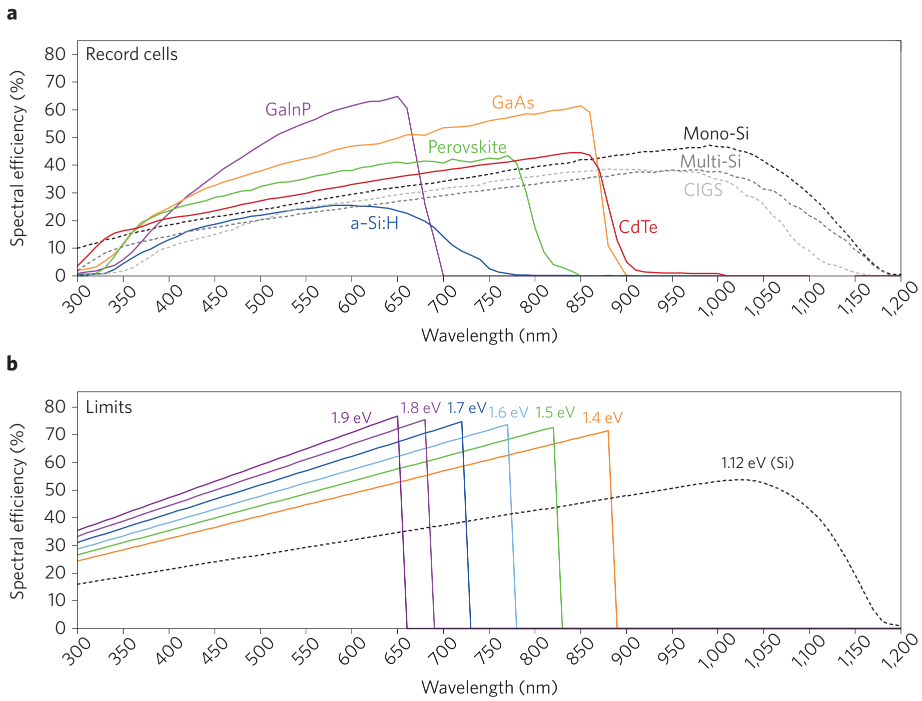

Figure 2 | Using spectral efficiency to choose tandem pairings. **a**, Spectral efficiencies of record PV cells that are candidates for top (solid) and bottom (dashed) cells. Data digitized from the solar cell efficiency tables[4]. **b**, Limiting spectral efficiencies of ideal top cells — calculated with a detailed-balanced model that considers radiative recombination only — and the ideal silicon bottom cell — calculated with a model that includes Auger recombination and Lambertian light trapping[5].

cell alone. Conversely, GaInP, which has a similar bandgap to a-Si:H, can provide a substantial efficiency boost if coupled with silicon so that wavelengths shorter than 650 nm are absorbed in the GaInP cell.

Picking partners

The maximum efficiency of a tandem can be calculated by summing the integrated sub-cell spectral efficiencies, each weighted by the spectra reaching that sub-cell and normalized to the incident photon power:

$$\eta_{\text{tandem}} = \frac{\int \eta_{\text{top}}(\lambda)\, f_{\text{top}}(\lambda)\, I(\lambda)\mathrm{d}\lambda}{\int I(\lambda)\mathrm{d}\lambda} + \frac{\int \eta_{\text{bottom}}(\lambda)\, f_{\text{bottom}}(\lambda)\, I(\lambda)\mathrm{d}\lambda}{\int I(\lambda)\mathrm{d}\lambda} \quad (3)$$

with

$$f_{\text{top}}(\lambda) = \frac{\Phi_{\text{top}}(\lambda)}{\Phi_{\text{incident}}(\lambda)} \qquad f_{\text{bottom}}(\lambda) = \frac{\Phi_{\text{bottom}}(\lambda)}{\Phi_{\text{incident}}(\lambda)} \quad (4)$$

In equation (4), $f(\lambda)$ is the (wavelength-resolved) spectral fidelity — the fraction of the incident light with wavelength λ that reaches a sub-cell (Φ is photon flux). The efficiency given by equation (3) is that of a tandem composed of two existing cells coupled losslessly. This means no electrical losses (for example, due to imperfect current matching), and thus implicitly assumes a four-terminal configuration, as well as no optical losses (for example, due to parasitic absorption). All tandems, regardless of their coupling configurations, are subject to the maximum efficiency constraint expressed by equation (3). Two-terminal tandems will likely fall below this limit primarily because of electrical losses, whereas four-terminal tandems will likely suffer primarily from optical losses.

There are two common assumptions for the limiting spectral fidelities. For a mechanically stacked tandem, $f_{\text{top}}(\lambda) = 1$ (all light reaches the top cell) and $f_{\text{bottom}}(\lambda) = T_{\text{top}}$ (all light transmitted through the top cell reaches the bottom cell). For two cells coupled with a beam splitter, $f_{\text{top}}(\lambda) = 1$ for λ shorter than $\lambda_{\text{top=bottom}}$ (the wavelength at which the top- and bottom-cell spectral efficiencies are equal) and 0 for longer wavelengths, whereas $f_{\text{bottom}}(\lambda) = 0$ for λ shorter than $\lambda_{\text{top=bottom}}$ and 1 for longer wavelengths. In other words, the beam splitter is perfect.

Table 2 lists the maximum efficiencies of tandems made from the cells in Fig. 2a using the $f(\lambda)$ values corresponding to the two coupling cases described above: mechanical stacking and beam splitter. One surprise is that the best perovskite cell on the best monocrystalline silicon cell results in only a marginal gain in efficiency (approximately 4% absolute) when the two sub-cells are coupled losslessly, yielding a tandem that just reaches 30%. As there will undoubtedly be at least optical losses in their coupling, it will be challenging to significantly exceed the efficiency of the silicon cell alone (25.6%) using present perovskites. An exception is if the sub-cells are coupled optically with an excellent beam splitter — see the 28.0%-efficiency tandem in Table 1— but this configuration is usually regarded as a laboratory demonstration that will not be manufactured and that will not collect diffuse light. Note, however, that the best perovskite cell with the best multi-crystalline silicon cell reaches nearly as high an efficiency and offers a substantial boost compared to the inexpensive multi-crystalline silicon cell alone (21.3%). Another surprise is that, of all existing PV

Table 2 | Maximum possible efficiencies of silicon-based tandem PV cells pairing existing record top and bottom cells.

Top cell	AM1.5G efficiency (%)	Bandgap (eV)	Fraction of detailed-balance efficiency (%)	Tandem efficiency with record mono-Si cell* (%)	Tandem efficiency with record multi-Si cell* (%)
GaInP	20.8	1.81	77	34.5 (35.1)	32.1 (32.6)
GaAs	28.8	1.42	87	34.9 (35.5)	33.6 (34.2)
CdTe	21.5	1.45	66	27.3 (27.7)	26.0 (26.4)
Perovskite	20.1	1.47	62	29.2 (30.2)	27.4 (28.4)
Perovskite	17.1	1.75	61	29.0 (29.7)	26.8 (27.5)

*The efficiencies in parentheses correspond to mechanical stacking; those not in parentheses correspond to coupling with a beam splitter. The V_{OC} of the silicon cell was adjusted to account for filtered illumination.

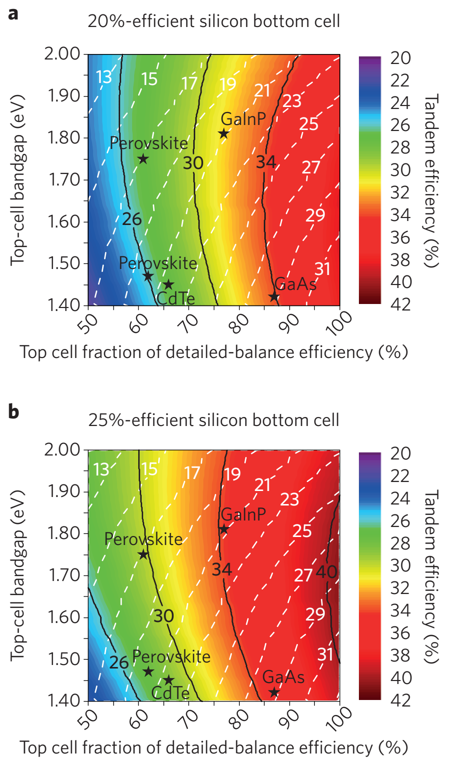

Figure 3 | Guide for predicting the maximum possible efficiency of a silicon-based tandem as a function of the top-cell bandgap and efficiency. **a**, Tandem with a silicon bottom cell that is 20% efficient when measured alone. **b**, Tandem with a silicon bottom cell that is 25% efficient when measured alone. In each plot, the color scale and black contour lines indicate the tandem efficiency, and the dashed grey contour lines indicate the efficiency of the top cell when measured alone. To obtain the approximate spectral efficiencies of the sub-cells used to calculate the tandem efficiency, the limiting spectral efficiencies in Fig. 2b were derated by scaling them by a constant factor.

cells, GaAs would make the best top cell, even though it has the 'wrong' bandgap according to Fig. 1b. This is because it is much more efficient — that is, closer to its detailed-balance limit — than the other cells.

Tomorrow's top cell

In evaluating new tandem possibilities, we believe that the best approach is to calculate the maximum tandem efficiency using the measured spectral efficiencies of the two cells of interest, as in Table 2. It is also possible, however, to construct a top-cell design guide using approximate spectral efficiencies calculated by derating the limiting spectral efficiencies shown in Fig. 2b. Here, derating indicates that the spectral efficiency is multiplied by a constant factor less than unity; that is, $\eta_{\text{derated}}(\lambda) = C\,\eta_{\text{limiting}}(\lambda)$ with C the 'top-cell fraction of detailed-balance efficiency'. According to equation (1), this is equivalent to reducing the V_{OC} or FF of an ideal cell, or reducing its $J_{SC}(\lambda)$ by the same fraction at each wavelength. Figure 3 is such a guide and predicts the efficiencies of tandems that pair a 20%- or 25%-efficient silicon bottom cell with top cells of varying bandgap and efficiency derating. The derating is expressed on the x-axis as the fraction of the detailed-balance efficiency, and the one-sun efficiencies of the top cells are given by the gray contours.

Although Fig. 3 is approximate, it successfully reproduces the exact results for existing sub-cells. For example, consider the GaInP cell in Fig. 3b, which assumes a 25%-efficient silicon bottom cell that is similar to the 25.6%-efficient record cell in Table 2. The star, which was placed based on the InGaP cell's bandgap and efficiency relative to the detailed-balance limit, corresponds to both the correct top-cell one-sun efficiency (slightly less than 21%, from the gray contour lines) and the tandem efficiency (slightly over 34%, from the color contours). This indicates how to use this guide to quickly evaluate candidate top cells: Find the cell's bandgap on the y-axis and its one-sun efficiency with the gray contours (or its fraction of the detailed-balance limit on the x-axis — the result is the same). The color then indicates the maximum tandem efficiency possible if this cell were coupled with a 20%- or 25%-efficient silicon bottom cell.

The future of silicon-based tandems is presently wide open, with several top-cell contenders fighting cost-performance trade-offs, and with new top-cell materials to emerge. Spectral efficiency, which allows cells to be compared at each wavelength on an equal footing, provides a means to assess the efficiency potential of any cell pairing, and thus a methodology for selecting top cells for silicon. At present, only III-V and perovskite top cells have reached efficiencies that justify coupling with the best silicon cells, with the former promising up to 5% higher absolute tandem efficiency than the latter. However, this picture will evolve as wide-bandgap cells continue to develop. Spectral efficiency will serve throughout this process as an unerring arbiter of cell pairings and a tool with which tandem efficiency limits may continually updated. ❐

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